AN UNDERWATER PASSIVE ACOUSTIC SERIOUS GAME TO RESEARCH EMPATHETIC ARTIFICIAL INTELLIGENCE

Madalin Facino	University of Bath
Andrei Vladescu	University of Bath
Christof Lutteroth	University of Bath
Alan Hunter	University of Bath
Aaron Roberts	Thales Underwater Systems
Samantha Dugelay	Thales Underwater Systems

1 INTRODUCTION AND BACKRGOUND

As submarine sensors grow increasingly advanced, managing escalating data volumes and pressure for command teams will be crucial. This surge in data is likely to heighten operator workloads as it necessitates thorough analysis and integration into the tactical overview[60]. Workload, in this sense, can be understood as the balance between the mental processing demanded by a task and the operator's capability to manage this demand[18 19]. Maintaining an optimal cognitive arousal level is vital[8]; overstimulation, or cognitive overload, can result in risk-taking behaviors[38], disordered task execution[19], delayed task completion[5], overlooked secondary tasks[49], vigilance decrement[36], diminished performance[34], and, in severe cases, complete performance failure[19]. Historical incidents, like the 2015 collision between the stern trawler Karen (B317) and a Royal Navy submarine, underline the grave consequences of operator overload[30].

Sonar operations in underwater settings face unique challenges due to complex marine conditions, weak signal reception compounded by strong background noise, and significant interference—all of which degrade communication quality and complicate underwater object detection[47 62 63]. These conditions are exacerbated by high transmission delays, limited bandwidth, and the energy constraints of underwater sensor nodes[58]. Further, the psychological toll on sonar operators is profound. The complexity of natural sonar targets generates multiple echo points, increasing the cognitive demands of distinguishing between actual targets and clutter[39 52 61]. Long-term exposure to such intricate auditory signals can affect operators' psychological well-being, evident in changes to auditory event-related potentials[32]. These factors, combined with the inherent stress of submarine environments[50], intensify the psychological strain on operators[55].

Whilst the collaboration between sonar operators and artificial intelligence (AI) is becoming increasingly necessary with data growth, distrust in AI technologies remains a major obstacle[22 26 37]. This paper proposes a method for testing a novel strategy to alleviate these psychological impacts and trust barriers through the development of empathetic AI. We suggest that integrating empathy into AI could foster trust, thereby enhancing the team dynamic, team performance, and reducing operator cognitive load.

To explore this hypothesis, we have developed a serious game within the Unity platform, simulating realistic sonar operation conditions. This game focuses on key psychological and cognitive factors involved in sonar operations whilst utilizing established acoustic models and physics[1,6,59]. The game design is centered around tasks that involve perception, multitasking, and stress management, ensuring that our study maintains ecological validity[57].

Submarine sonar operations pose a triad of formidable challenges for operators: multitasking, perception, and pressure management, each significantly affecting operational efficiency and psychological well-being[25,57]. The intense demands of multitasking require operators to simultaneously process varied acoustic signals, maintain situational awareness, communicate findings, and make pivotal decisions. This cognitive burden, as underscored by findings using NASA's Task Load Index[18,19], highlights the pressing need for innovative tools designed to alleviate these pressures.

The perceptual challenges in sonar operations are equally daunting. Operators must distinguish critical signals from pervasive background noise within a complex underwater soundscape[53]. This task demands not only technical acumen but also continuous cognitive engagement. Additionally, the high-pressure conditions inherent in submarine operations—characterized by extended submersion, erratic sleep patterns, and high-stakes decision-making – intensify psychological stress, potentially undermining both performance and mental health[50].

Current training simulations like MATB[45] and the naval warfare simulation game Dangerous Waters[43] offer foundational frameworks but do not fully address these multifaceted challenges. MATB focuses primarily on procedural and multitasking skills but offers limited insight into the perceptual complexities of sonar operations. Dangerous Waters, while providing an intricate portrayal of naval engagements, is constrained by its complexity and steep learning curve, which may impede its effectiveness in psychological impact studies focused on specific cognitive and emotional responses. Critically, these platforms do not incorporate biosignal monitoring, a key aspect in assessing physiological markers during operations[16,17,21] which will serve to inform an empathetic response.

Recognizing the state-of-the-art in current underwater acoustic training tools, there is a critical need for a simulation that not only represents the acoustic and operational conditions of sonar operations but also serves as a dedicated medium for studying psychological impacts. Our proposed serious game environment, which will integrate empathetic AI, is designed to address this need. By recognizing and responding to human emotions, empathetic AI holds the promise of enhancing human-machine collaboration. This innovative integration could reduce cognitive load, improve perceptual accuracy through adaptive interfaces, and alleviate operational pressures by offering psychologically attuned support. Furthermore, the efficacy of serious game environments in such applications has been substantiated in an extended abstract we published in the ACM Library through the First International Symposium on Trustworthy Autonomous Systems (TAS23)[13].

This interdisciplinary effort combines psychology, computer science, and engineering to not only test our hypotheses about empathetic AI but also to facilitate the development of more intuitive and empathetic user and AI interfaces. By simulating representative real-world conditions within a controlled setting, we aim to provide insights that could lead to significant advancements in human-machine collaboration.

2 DESIGN AND DEVELOPMENT OVERVIEW

Our serious game, based in Unity due to its robust framework and relative ease of use, is currently in its prototyping and refining stage. It simulates the critical aspects of submarine sonar operations for psychological studies — balancing acoustic realism with an examination of psychological impacts. Central to the game's narrative is a mission to intercept submarines, depicted as 'poachers' using active sonar, which poses a threat to whale populations[35]. This scenario frames the gameplay within realistic operational tasks while avoiding sensitive real-world conflicts.

2.1 User Interface and Aesthetic Choices

The user interface harmonizes the roles of sonar operator (SOP), officer of the watch (OOW), and target motion analyst (TMA)[18 49], presenting operators with an array of interactive tools. Operators navigate through a time-bearing chart for real-time tracking of acoustic signals (left side of Figure 1), employ a top-down submarine view to direct the sonar beam (center of Figure 1), and utilize a spectrogram (right side of Figure 1) for intricate sound frequency analysis. Additionally, operators will wear headphones during the study and will be able to listen to the audio being displayed on the screen and hear it being impacted by their inputs in real-time. The game offers operators the option to make the weighted decision of apprehending the target (upper center of Figure 1), pushing them to fully ensure their selected entity is in fact a target. Tactical decision-making is enhanced through the use of trackers to label potential targets (upper left of Figure 1). The interface is complemented by an oracle AI system that proposes classifications and tracks for the acoustic signals, which players can adjust, fostering engagement and gradually building trust in the technology.

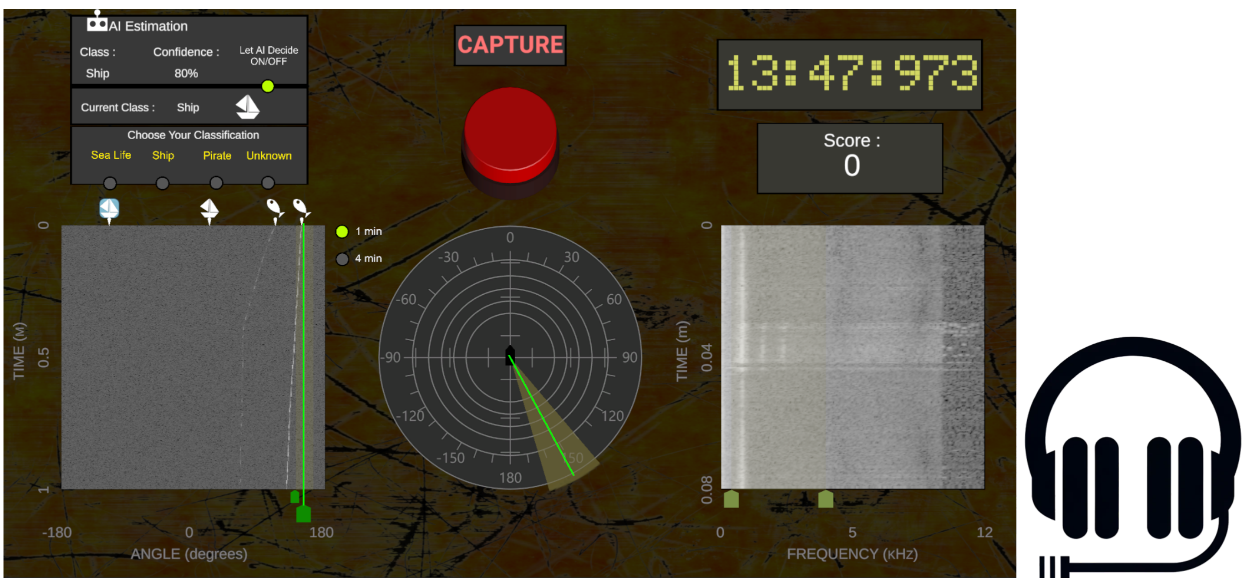


Figure 1: Game Interface

Aesthetically, the game uses gamified symbology and coloring to facilitate accessibility for university participants. Future iterations will incorporate NATO standard colors and symbols[3] and will utilize fonts optimized for readability[63]. Color schemes are carefully chosen to induce stress during critical gameplay moments[20 29 44], such as red flashing lights as the timer runs down, maintaining a balance between challenge, gamification, and realism.

2.2 AI Design and Evolution

The AI in the game is an Oracle (or all knowing) in order to maintain total controllability and replicability. We degrade the performance of the Oracle intentionally to simulate realistic AI behavior. It serves as an informed assistant, having a comprehensive overview of the game state and aiding in sound identification and classification. Initially, the AI marks potential tracks on the time-bearing chart with varying degrees of pre-programmed confidence[12] in relation to the given scenario, encouraging players to interact with and trust[12] the AI's judgment through transparency[56]. This feature is designed to be user-overridable, allowing for dynamic interaction and gradual trust-building in the AI's capabilities. Feedback from initial pilot sessions will guide the AI's development, particularly toward integrating more sophisticated empathetic responses. Future enhancements will include the necessary integration of an empathetic feedback loop. Our AI currently works without a feedback loop for piloting purposes but a crucial step in developing our environment for impact studies will be to integrate a biosignal feedback loop — which has been designed and validated by colleagues at the University of Bath and which will be published at CHI2024[11]. With such integration, we will be able to have our AI change its form of support depending on the operator's cognitive state. Additionally, we plan to integrate more advanced intentional AI performance variability, such as occasional failures and uncertainties in distinguishing between whale calls and other sounds[48] or more regular changing of confidence, to enrich the training scenario, better understand the impact of performance on trust, and better mimic real-world conditions.

2.3 Ecological Validity and Scenario Design

To ensure ecological validity while focusing on the psychological impacts, the simulation strategically omits extraneous technical details that do not directly contribute to our core research objectives. This simplification allows us to concentrate on critical cognitive domains relevant to sonar operations —perception, multitasking, and stress management[57] — without overwhelming operators with unnecessary information.

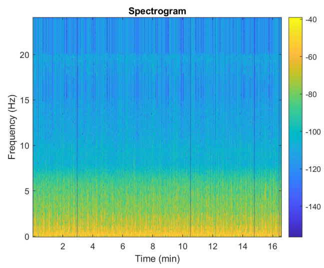
The game is designed to simulate varying degrees of operational demand and stress[18]. Scenarios increase in complexity and environmental pressure, challenging the operator's cognitive load and decision-making abilities under different stress levels. Stress-inducing events are carefully timed to test the operator's ability to maintain situational awareness and make precise judgments, reflecting the pressures of real sonar operations. A scoring system mimics the high stakes of operational decisions, where errors can lead to significant consequences[42].

Through these structured design elements, the simulation serves both as a technological and psychological exploration tool, and as an immersive representation of the challenges faced by sonar operators. This deliberate design ensures that the environment is not only a test bed for advanced AI interactions but also a platform for operational and psychological research.

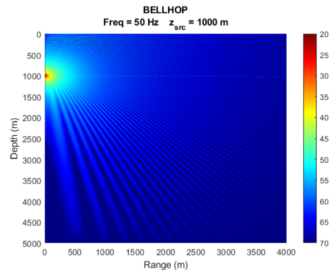
3 TECHNICAL IMPLEMENTATION

3.1 Pre-Processing

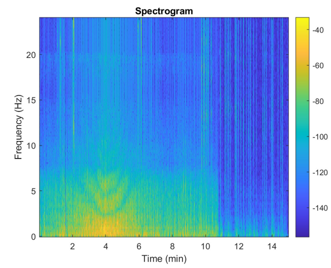
Prior to the start of the simulation, pre-computation is undertaken to ensure accurate acoustic modeling and integration into the Unity environment. Each entity — whether it be a ship, target, or marine life — is assigned a specific audio signal (.wav file) selected from an underwater acoustic database[2 10 24 46]. These entities are given defined paths relative to a stationary submarine, as depicted in Figure 3, which



(a) North Atlantic Right Whale 'Scream' Signature



(b) Munk Propagation Model in Bellhop



(c) Propagated Signature

Figure 2: Propagation Model[54] Example.

are plotted to ensure realistic spatial navigation. The audio for these entities is adjusted using a validated Bellhop propagation model[40 54], which applies the Munk sound speed profile[1] to realistically reflect the sound propagation across various environmental conditions such as distance, depth, and sound speed. The effects of the propagation model can be seen in Figure 2(c) (in relation to Figure 3) as the sound of the whale intensifies in the first few minutes as it approaches the submarine and then dissipates as the whale moves further away.

Following the path definition for each entity, we establish the AI's behavior in advance, programming it to react with varying degrees of confidence to different audio characteristics as they unfold within the scenario. By pre-setting the AI's confidence levels[12] at timed intervals, we simulate a dynamic and realistic response to complex acoustic environments. For instance, the AI's confidence in identifying a source might be programmed to decrease when that source crosses paths with another entity, reflecting the increased difficulty in distinguishing between overlapping acoustic signals[28] (see Figure 3). This aspect enhances the simulation's realism, providing players with a more nuanced and challenging interactive experience.

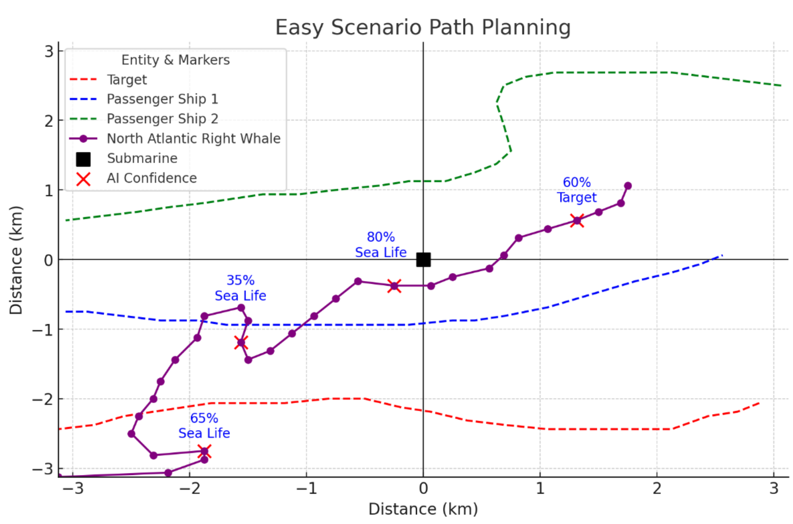


Figure 3: Path Planning Process for First Pilot Run

In addition to source handling, ambient noise modeling is also a crucial part of the pre-computation. Noise power spectral density[9], based on the Wenz curves[59] for a given sea state, is used to generate a consistent audio signal for the ambient noise. This ensures the noise complements the dynamic acoustic environment of the simulation, providing a realistic background of sea-state-specific sound.

3.2 Real-Time Computation

Once the pre-computation is complete, the simulation transitions to real-time execution within Unity, where these elements are dynamically integrated to create an immersive user experience. Each precomputed audio source and noise signal is introduced into Unity as an "AudioEntity" object. The relative positions of these sources are translated into Unity units, mapping the realistic 3 x $3\ \mathrm{km}$ world region onto a 100 x 100 unit grid within the game environment. Unity's native sound propagation model is disabled in favor of our precomputed data, which is tailored to offer a more sophisticated and accurate acoustic representation.

During gameplay, players can adjust settings such as the sonar beam's direction, width[27], and bandwidth[51]. These user inputs dynamically influence the audio processing of both the source signals and ambient noise, reflecting the changes in the acoustic environment in real time. The modification of the sonar settings adjusts the visibility of sources and the level of noise based on the beam's width and the selected frequency bandwidth.

This dynamic scaling is also applied to the ambient noise AudioEntity (which is anchored to the center of the beam to maintain consistent noise through Unity's audio listener), ensuring that the noise levels and source visibility are appropriately adjusted according to the player's settings. All of our AudioEntities are then put into the environment and are heard and displayed on the spectrogram, through Unity's spectrogram fucntionality, when within the user-selected beamwidth and bandwidth.

The real challenge arises in handling the time-bearing plot, which is not natively supported by Unity. For each time interval, signals extracted from the real-time spectrogram are allocated to appropriate bearing bins to visually represent the directionality and intensity of underwater sounds. Gaussian noise[23], generated based on the variance calculated from the adjusted noise level, is artificially introduced to simulate realistic ambient noise in the time-bearing plot.

The integration of precomputed acoustic data and the real-time dynamic adjustments in Unity form the backbone of our simulation. This sophisticated approach ensures a high fidelity simulation that is both immersive and scientifically based, enhancing the realism and educational value of the acoustic experience.

4 HUMAN FACTORS AND COGNITIVE DOMAINS

4.1 Studying Operator Engagement and Trust in Automated Systems

Our simulation aims to provide a unique perspective on human-machine interaction, particularly in the specialized domain of underwater acoustics. It offers a platform for studies into how operators engage with sonar interfaces and AI systems, focusing on key psychological aspects such as trust, reliance, and the effectiveness of AI in supporting complex decision-making processes and reducing cognitive overload[8,41]. By integrating biosignal and eye-tracking technologies[7], alongside thorough post-study analyses, we will be able to measure when and how operators respond to AI recommendations. This data will then be used for developing optimal strategies for human-machine collaboration, and for understanding the broader implications on user fatigue, performance, stress, and cognitive load[16 17 21 33].

4.2 Analyzing the Impact of Empathetic AI

At the heart of our research lies a deep analysis of the psychological stressors inherent in submarine sonar operations. The serious game simulates these high-pressure environments, providing a controlled laboratory for studying the impacts of multitasking, perceptual challenges, and operational stress on psychological well-being. By varying environmental complexity and levels of AI support, we plan to methodically assess their effects on cognitive load[14], stress, and operator performance. In the future we may additionally work to further replicate such stressful conditions by creating more immersive sensory environments outside of the simulation[17 31].

Empathetic AI stands as a cornerstone of our experimental framework, aimed not only to enhance contact identification and classification but also to adjust its responses based on real-time operator monitoring. Our research design will critically examine three distinct conditions — no AI, neutral AI, and empathetic AI — to ascertain the potential of empathetic AI in enhancing human-machine collaboration. This design will be repeated with different expressions of empathy to build upon our understanding. Our aim is to provide support that is both perceptively and psychologically attuned to the operators' needs, thus fostering more effective and intuitive human-machine interactions — building trust[15] and a more optimal human-machine team dynamic.

Upon the completion of initial piloting phases, our first primary study will implement a within-subjects design, engaging a diverse cohort of at least 60 participants to ensure a broad analysis across various conditions, thereby maximizing ecological validity. The study will be a 3 x 2 design using the above experimental conditions — at both low and high demand to evaluate the effects of empathetic AI integration on operational performance. We will adopt a continuous gameplay approach which moves beyond traditional win/lose frameworks by allowing participants to accumulate points that influence their financial compensation[42], thereby adding a realistic element of performance-related stress. A preliminary phase will familiarize participants with the game mechanics before formal data collection commences to ensure there is no practice effect[4] acting as a confounding variable, supported by a detailed screening questionnaire to control for factors such as experience level and personality traits — ensuring methodological rigor.

5 CONCLUSION

In conclusion, the integration of an acoustic model into the Unity environment has been successfully achieved, with an interface that carefully aims to balance realism, gamification, and ecological validity. The implemented scenarios and interface are crafted to maintain this equilibrium, providing a foundation for ongoing refinements through initial testing phases. This work not only sets the stage for future investigations into the efficacy of empathetic AI but also employs an oracle AI as a proxy, simulating behaviors that pave the way for the development of future empathetic AI systems. These efforts collectively work to ensure a comprehensive exploration of how psychologically-attuned AI can enhance human-machine interactions in complex decision-making environments.

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